The University of Chicago

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A DISSERTATION SUBMITTED TO THE FACULTY
OF THE DIVISION OF THE PHYSICAL SCIENCES
IN CANDIDACY FOR THE DEGREE OF DOCTOR
OF PHILOSOPHY

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STRUCTURAL PETROLOGY OF THE BARABOO QUARTZITE

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ABSTRACT

The microstructures of the Baraboo quartzite of Columbia and Sauk counties, Wisconsin, have been studied from oriented hand specimens, polished sections, and thin sections. Fabric axes, determined from the pole patterns of the deformation lamellae, vary consistently over the region and are not related to the bedding or the macrofoliation. Because of this variation, the deformation lamellae have been assigned to a deformation later than the major folding of the region. In addition, the character of the deformation lamellae themselves and the type of pole pattern have been used as a qualitative index of the intensity of the deformation. Microfractures are common features of the quartzite; they exhibit a strong preferred orientation and are geometrically related to the deformation lamellae. Quartz deformation bands are described, named, and correlated with bedding-plane shear. Quartz optic-axes fabrics are weak and difficult to interpret.

INTRODUCTION

The present work is a field study of the outcrops and laboratory examination of oriented hand samples, polished sections, and thin sections of the Baraboo quartzite of Columbia and Sauk counties, Wisconsin. It is not my purpose to attempt a solution of the fundamental problem of the dynamics of quartz deformation or the mechanics of tectonic movements but rather to shed further light on the qualitative description of the processes of deformation and their correlation with the macrostructures observed in the field.

GENERAL GEOLOGIC DESCRIPTION OF THE BARABOO REGION

The Baraboo quartzite crops out in Columbia and Sauk counties, Wisconsin. Its structure (Fig. 1) is a complex canoe-shaped synclinorium, whose major axis strikes approximately N. 70° E. and is roughly 25 miles east-west and 9 miles north-south. The outcrop area can be conveniently divided into a north, a south, and a west range. In the north range the bedding is mainly vertical, striking east-west, with the tops of the beds to the south; in the south range it dips 20°–40° to the north, striking N. 70° E.; the much shorter west range is an area of complex, rather right, east-west folds, plunging eastward. In the western half of the south range, a series of gentle folds, trending N. 60° E., truncates the larger structure.

The Baraboo area is of considerable geologic interest because of excellent exposures of axial-plane cleavage, drag folds, etc. Numerous papers concerning the various aspects of the region have appeared in the literature. The most comprehensive treatise on the area and one with considerable emphasis on the structure of the quartzite ranges ap-

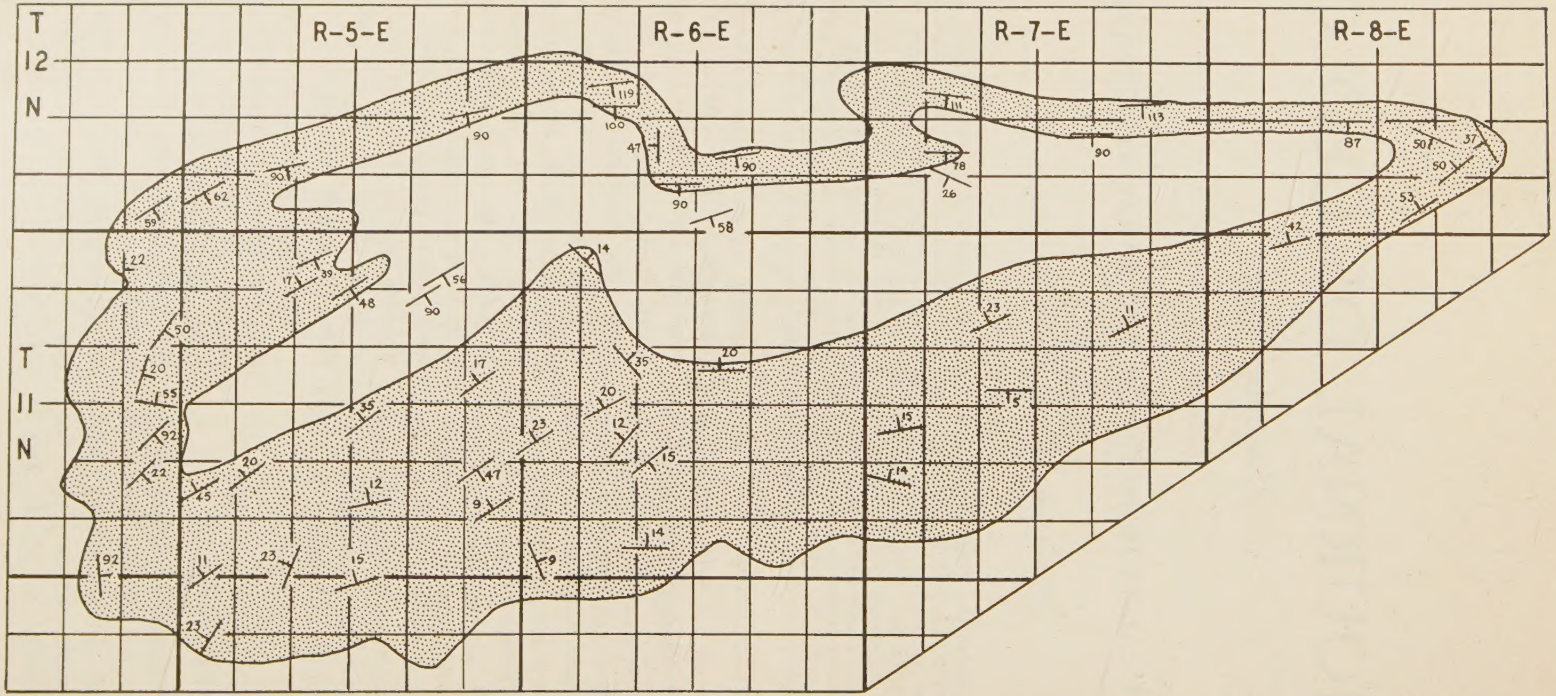

FIG. 1.—Generalized outcrop area of the Baraboo quartzite (modified from A. Leith), showing bedding orientation for selected representative locations. The four outcrops in the interior of the basin are possible outcrops of the Dake quartzite.

peared in 1904 by Samuel Weidman.[1] For the details of the region reference must be made to Weidman's work. It is sufficient to say that Weidman correctly placed the Baraboo quartzite in the Huronian, described the structure as a complex synclinorium, and divided the Huronian sediments into three formations: the Baraboo quartzite, the Seeley slate, and the Freedom iron formation. The latter two formations, which are above the Baraboo quartzite, do not crop out in the region and were described by Weidman from mine workings.

Andrew Leith[2] restudied the earlier unpublished commercial reports of C. L. Dake and in 1935, on the basis of Dake's descriptions of drill cores, divided the Baraboo Huronian sediments into an upper and lower part. Leith's pre-Cambrian column is as follows:

Algonkian	Upper Baraboo series	Rowley Creek slate Dake quartzite
	Unconformity (?)	
	Lower Baraboo series	Freedom formation Seeley slate Baraboo quartzite
	Unconformity	
Archean		Rhyolite, tuff, granite (some granite may be intrusive into the Baraboo series)

A short description of the formations of the lower Baraboo series, taken from Weidman's[3] publication, is given below:

The Baraboo quartzite exceeds 4,000 feet in thickness and is composed almost entirely of monocrystalline sedimentary quartz grains with varying admixtures of fine-grained sericitic material. Interstitial iron oxide imparts a reddish color to much of the formation. Detrital hematite and zircon grains are locally important. All large quarries in the Baraboo quartzite exhibit thin layers of almost pure sericitic material, varying in thickness from a few centimeters to several feet, interbedded with massive quartzite. Some of these thin beds are pinched into lens-shaped bodies. A poorly developed basal conglomerate is present in one known locality. Intraformational pebble bands of vein quartz are common features of the massive quartzite.

The Seeley slate is not known to crop out in the region and is recognized only in mine workings and drill holes. Its material is observable at present on the dumps of old mines and is a finely banded, soft slate, exhibiting excellent axial-plane cleavage. The thickness of the formation is unknown.

The Freedom formation is the iron-bearing formation of the region. It does not crop out in the area. Weidman describes the formation as composed of slate, chert, dolomite, iron ore, and all

[1] "The Baraboo Iron Bearing District," *Wis. Geol. Nat. Hist. Surv., Bull. XIII, Econ. Ser. No. 8* (1904), pp. 1–190.

[2] "The pre-Cambrian of the Lake Superior Region, the Baraboo District, and Other Isolated Areas in the Upper Mississippi Valley," *Ninth Ann. Field Conf. Kan. Geol. Soc.* (Wichita, Kan.: Kansas Geological Society, 1935), pp. 320–32.

[3] Pp. 22–29 of ftn. 1.

gradations among these types. The thickness of the formation is unknown but is estimated by Weidman to exceed 1,000 feet.

Leith,[4] utilizing Dake's data, named and described the formations of the Upper Baraboo series as follows:

> Rowley Creek slate: This slate does not outcrop. . . . . It occupies the middle of the synclinal trough. . . . . Its thickness varies between 40 and 149 feet. . . . .
>
> Dake Quartzite: This formation was encountered at 42 diamond drill holes. . . . . It varies in thickness up to a maximum of 214 feet. . . . . Lithologically, it consists of a coarse grained quartzite which contains a large amount of sericite and chlorite as a matrix to the quartz grains. A large portion of the formation is coarsely conglomeratic with large, and sometimes angular, pebbles. . . . .
>
> The quartzite is not known to outcrop, but the writer believes that one, and possibly several, surface exposures formerly thought to be Baraboo quartzite are of Dake quartzite. . . . .

Leith points out that two features of the structure indicate an unconformity between the Upper and the Lower Baraboo series. The drill records show that the Dake quartzite bevels the underlying Freedom formation; and, if the surface outcrops of the Dake are correctly identified, they dip at gentler angles than does the underlying exposed Baraboo quartzite. An example of the latter is Sample 55, Figure 14, which is the "type" surface exposure of the Dake. The bedding here dips approximately 25° southward, while a short distance to the north the bedding in the Baraboo quartzite is roughly vertical (the symbols used in all illustrations are explained in Fig. 2).

An attempt was made in the present study to determine fabric differences between the Dake and the Baraboo quartzites in the above outcrops in the hope that fabric differences would show the unconformity. No evidence was obtained from the mircofabric studied either to substantiate or to refute the presence of the unconformity. The fabric axes determined from the pattern of the poles of the deformation lamellae (discussed in detail later in the paper) of both outcrops are similar.

Another problem associated with the structure is the determination of the number of deformations that the Lower Baraboo series has undergone. To begin with, it appears unlikely that the complexities of structure encountered in the Baraboo quartzite could be derived in one simple deformation. Evidence is submitted that the Lower Baraboo series has suffered at least two deformations. If the angular unconformity between the Upper and the Lower series is admitted, then the region has been subjected to at least three deformations since Lower Baraboo times.

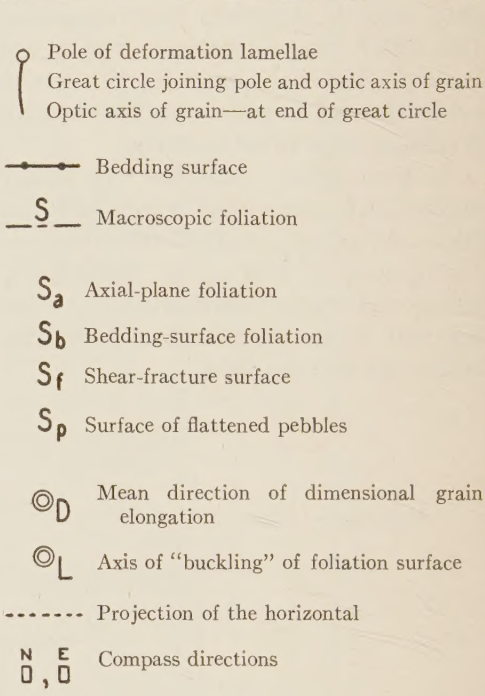

FIG. 2.—Symbols used on all maps and projections

[4] Pp. 329–30 of ftn. 2.

Volcanics, basal to the Baraboo series, occur locally around the perimeter of the synclinorium. These outcrops were not studied in detail and will not be discussed in this paper.

Resting unconformably on the Baraboo series are Upper Cambrian sands. They are roughly horizontal and crop out both in the interior of the synclinorium formed by the Baraboo series and on all sides. Several small-scale faults are found in these Cambrian sands in the interior of the synclinorium. The displacement along the fault planes can be measured in inches, the strike is roughly east-west, and the downthrow side is toward the interior of the basin. For these reasons the Paleozoic faulting is attributed to differential compaction of the sediments, and no major Paleozoic or later deformation is recognized.

The difficulties in determining the field structural relations in the Baraboo quartzite are the absence of any traceable horizon within the quartzite, the difficulty in recognizing tops and bottoms of bedding surfaces, and, in many examples, difficulties even in determining bedding surfaces. The quartzite varies tremendously in its degree of deformation over small distances. Many massive outcrops exhibit apparently undeformed ripple-marked surfaces, while a few tens of feet away stratigraphically, in more sericitic layers, large-scale drag folding and pronounced boudinage occur.

An enumeration of the principal macrostructural features follows:

1. Bedding surfaces are identified both where the change in lithology with respect to amounts of admixed sericite is gradational and where it is abrupt. Cross-bedding surfaces are easily confused with true bedding in small outcrops, and small errors in the orientation of the bedding surfaces are expected.

2. Axial-plane foliation is pronounced in the thicker layers, which contain considerable amounts of sericite. It is found only in the north range, where the bedding is close to vertical. The orientation of this foliation is roughly N. 60°–80° E., dipping 40°–60° N.

3. Bedding-plane foliation is found in the more massive layers in the north range and is the principal foliation of the south range.

4. Shear-fracture surfaces can be divided into the following types:

a) Shear fractures in massive quartzite that are observed to pass into axial-plane foliation in the more sericitic layers.

b) Chevron folding of the axial-plane foliation is locally observed. This type of structure has been described by Barrow,[5] who calls these acute plications "buckling." Fracture at the crests and troughs of the buckling and small displacements along the fracture surfaces are readily observable. The amplitude and wave length of the buckling observed varies between 0.05 and 2.5 cm.

c) Shear fractures, discontinuous and continuous, in the more massive members transcend all other structures in the south and west ranges. These are roughly vertical and trend east-west. The formation of these shear fractures was apparently subsequent to all major deformation.

5. Metamorphic surfaces consisting of flattened pebbles are prominent in the outcrop at the locality of Sample 55, Figure 14. This is a quartzite outcrop which Leith said might be an exposure of the Dake formation.

6. Macrolineation is locally evidenced by the following factors:

[5] "On Buckled Folding," *Rept. Brit. Assoc. Adv. Sci.*, Vol. LXXXII (1912), pp. 473–74.

a) Intersection of axial-plane foliation and bedding
b) Intersection of shear fractures and bedding
c) Crests and troughs of the buckling
d) Slickensides

7. Quartz veining of several forms is recognized:

a) In the north and west ranges, veins of quartz varying in thickness from a few millimeters to about 60 cm. are common. These veins follow joint patterns and transect all metamorphic structures.

b) In highly deformed quartzites, deformed quartz veins are present. Some of these deformed veins are cut by planar veins.

c) Ladder veins of quartz are found in the competent members of large-scale drag folds. They can be interpreted as vein filling of tension fractures which are roughly perpendicular to the bedding.

d) S-shaped gash veins of quartz are very common. They have not been interpreted and have not been related to the regional structure

8. Large-scale drag folds are found in three outcrops near the top of the exposed Baraboo formation in the south range, near where Sample 20, Figure 14, was collected. Boudinage is well marked, both parallel and perpendicular to the dip of the bedding.

9. No large-scale faults are recognized in the field. Leith[6] places a north-south fault between Samples 58 and 38 of Figure 14. This fault was apparently based on drill records. If a large-scale fault is present, it is not represented in the pattern of the deformation lamellae, because the fabric axes determined from the pattern of these lamellae are similarly oriented in both the above samples, as well as in those samples farther west from the supposed fault. (Fig. 14.)

[6] Pp. 329 of ftn. 2.

Consistently throughout the area, roughly vertical, north-south shear joints or perhaps shear fractures are encountered. Slickensides on these surfaces are rare but are found frequently enough to assume some north-south adjustments by fracturing. It is interesting to note that these surfaces are subparallel to the *a*–*b*-fabric planes determined from the deformation lamellae.

MICROSTRUCTURES

I. SINGLE GRAINS

The principal intragranular microstructures include the following:

1. Secondary quartz enlargement of the original quartz grains is visible in many thin sections. The original boundary is visible because a thin film of impurities at the original grain surface is incased by the secondary enlargement. The above is true only in samples containing small amounts of sericite. Samples containing large amounts of sericite, however, rarely exhibit original boundaries of the quartz grains, but each grain is completely surrounded by sericite grains. These sericite grains appear to penetrate the boundaries of the quartz grains as if sericite had replaced quartz. An original boundary is rarely observed, but when it is, it can be seen that the original quartz grain has grown by secondary quartz enlargement and has incased the adjacent sericite grains.

2. Deformation, or Böhm, lamellae are frequently observed structures within individual grains. They commonly occur in the central portions of the grains and appear as a set of closely spaced subparallel planes which are slightly lens-shaped in cross section. Infrequently, two sets of deformation lamellae are found in the same grain. A historical summary of previous work on deformation lamellae and

a careful description of them has been given by Earl Ingerson and O. F. Tuttle.[7]

3. Undulatory extinction is present in nearly all quartz grains observed. The magnitude of this change in optic orientation varies tremendously from grain to grain in one sample and in different samples. In addition to this continuously varying position of the optic axis in a particular grain, discontinuities occur which divide the grain into bands subparallel to the optic axis. Anna Hietanen[8] has extensively described deformed quartz grains from the Finnish quartzites, and she considers the undulatory extinction as being due to bend-gliding along the basal pinacoid and the discontinuities subparallel to the optic axis as actual rupture planes.

4. Undulatory extinction discontinuities with apparently random orientation are observed as thin bands across the grain. They have a slightly different optical orientation and/or index of refraction from the rest of the grain and are, therefore, seen only when the grain is very close to an extinction position. Two sets of bands, whose traces tend to be perpendicular, are present in most grains showing the banding. These bands agree in appearance with structures in vein quartz observed by Sidney Adams[9] and are termed "deformation bands," following the usage in metallurgy.[10]

5. Sutured boundaries between quartz grains are common. An examination of variously deformed quartzites shows a wide variation in the character of the sutured boundaries. The individual sutures are definitely different in different samples; they are not necessarily perpendicular to the interface between grains; they vary in an individual grain according to the optic orientation of the neighboring grain, which makes the interface; and they exhibit marked differences in the amount of interpenetration. In examples in which the interpenetration is large, the sutured parts of both grains differ considerably in optical orientation from their parent-grains. All variations between no change in optic orientation of the sutured parts of the grains to considerable change are observed. This suturing of grain boundaries and then rotation of the sutured parts with recrystallization could be major processes in the breakdown of large grains. In addition to the above, differences in the amount of interpenetration of the sutures are observed in variously oriented sections of the same sample. This observation indicates that the character of the sutures is probably related to the major stress pattern. No investigation of suturing other than the above general observations has been made in this study.

Much less frequent than suturing is the "pressing-in" of one side of a particular grain into an adjacent one. In some examples it is possible to observe the complete original boundary of one of the grains and the partial original boundary of the other grain.

6. Breakdown of the original grains by deformation can be observed as having taken place

a) Along planes subparallel to the optic axis, where the original grains break down into needle-like fragments exhibiting strong undulatory extinction.

[7] "Relations of Lamellae and Crystallography of Quartz and Fabric Directions in Some Deformed Rocks," *Amer. Geophys. Union Trans.*, Vol. XXVI (1945), pp. 95–105.

[8] "On the Petrology of the Finnish Quartzites," *Bull. Comm. géol. Finlande, No. 122* (1938), pp. 1–118.

[9] "A Microscopic Study of Vein Quartz," *Econ. Geol.*, Vol. XV (1920), p. 648.

[10] Charles S. Barrett, *Structure of Metals* (New York: McGraw-Hill Book Co., 1943), pp. 305–7.

b) Along the sets of deformation bands, where the whole grain breaks down into small angular units that are roughly equant in cross section and vary slightly from one another in optic orientation. The end-result of this breakdown could result in the texture called "crushed quartz" by R. E. Fellows.[11]

c) At the boundaries among grains, where small sutured fragments are detached from their parent-grains.

d) In the interior and at the boundaries among grains, where recrystallization like that illustrated by J. A. Hedvall[12] occurs, that is, growth of new crystals at the expense of the old ones.

7. Small subhedral grains are found in the interstices among the larger grains. They show no trace of a rounded surface, have very irregular but equant shapes, and appear as if they had grown around new nuclei, that is, had recrystallized.

8. In some of the quartzites that contain negligible amounts of sericite and have suffered extensive deformation, as shown by the partial breakdown of the larger grains, very elongate quartz grains are observed. Rarely, one of these has an original sedimentary boundary, indicating that it formed from an original grain and was not the result of growth from a new nucleus or of coalescence of several grains. An elongate grain commonly exhibits marked discontinuities in the undulatory extinction subparallel to the optic axis when it is subparallel to the dimensional elongation. On the other hand, if the grain is dimensionally elongated subperpendicular to the optic axis, it may show well-developed deformation lamellae in addition to the discontinuities in the undulatory extinction. Samples of quartzites containing large amounts of sericite display little elongation of the original quartz grains of the sand size. These grains have reacted to the stress like a rigid body in a fluid medium.

[11] "Recrystallization and Flowage in Appalachian Quartzite," *Bull. Geol. Soc. Amer.*, Vol. LIV (1943), p. 1414.

[12] *Reaktionsfähigkeit fester Stoffe* (Leipzig: Verlag von Johann Ambrosius Barth, 1938), p. 53.

II. POLYCRYSTALLINE AGGREGATES

The principal intergranular microstructures of the Baraboo quartzite include the following:

1. Planar structures passing through more than one grain without deviation at the grain boundaries are commonly observed. Some of these are marked by thin veinlets of very fine-grained sericite. In most examples, however, they are discontinuous planes of inclusions. In all examples, continuous or discontinuous, these planes show a pronounced parallelism. More than one set of such structures can be identified in some samples. These planar structures are termed "microfractures."

2. Quartz microveins are common. They occur as planar structures and might be thought of as having grown along the microfracture surfaces described above. In addition, quartz microveins are found that could be described as "contorted." Both types have been found in the same thin section, with the planar veins cutting the contorted veins.

3. Microfoliation surfaces are visible in samples containing large amounts of sericite as concentrates of sericite cutting across relic bedding but not cutting through original quartz-grain boundaries.

4. Original sedimentary structures commonly observed in thin sections are the following:

a) Laminae of heavy mineral concentrates are recognizable in a large number of samples. These laminae are valuable

field aids for the determination of the sedimentation surface. They rarely exceed a few millimeters in thickness and are composed exclusively of hematite and zircon grains. Sufficient zircon grains could be found for a regional study of the zircon fabric.

b) Graded bedding is prominent on a microscale, and in most examples one graded unit represents one cross-bedding lamina.

c) Ripples and truncated ripples are visible in thin section by slight changes in grain size or by variation in abundance of hematite, zircon, or sericite.

d) Some polycrystalline (sedimentary) quartz grains are present in the more conglomeratic phases of the Baraboo quartzite. Some of the individual grains show a much higher degree of metamorphism as well as a greater variation in degree of metamorphism from grain to grain than is true for monocrystalline grains of the same size in the same sample. This variation indicates a source region or regions in which the quartzites differed widely in degree of metamorphism. As will be shown later in this paper, the region may be as small as the outcrop area of the Baraboo quartzite and still show this wide range in degree of metamorphism.

DETAILS OF THE MICROSTRUCTURE

I. DEFORMATION LAMELLAE

The deformation lamellae observed in the Baraboo quartzite agree in the main with those described by Ingerson and Tuttle.[13] Contrary to their findings in the Ajibik quartzite and in a biotite gneiss from near Washington, D.C., however, deformation lamellae are common in the Baraboo quartzite and are relatively easy to observe in the majority of examples. In samples containing so much sericitic material that the individual quartz grains are not in contact with one another, however, the readjustments during deformation have been made by the sericite grains leaving the quartz apparently undeformed and without deformation lamellae.

Various interpretations have been given to the deformation lamellae, but, following Ingerson and Tuttle, they can all be classified as: (1) planes of liquid inclusions, (2) healed fractures, and (3) translation glide-planes. Their exact nature is not known; their relation to quartz structure is obscure; and their orientation with respect to the major-stress axes is based on field evidence. Deformation lamellae have not been observed in laboratory deformation of quartz.

H. W. Fairbairn[14] measured the angle between the poles of the deformation lamellae and the optic axes of the same grain and found a total variation of from 3° to 85° with maxima at 18° and 27°. He interprets the deformation lamellae as translation glide-planes containing the glide-line $[m:r]$.

Ingerson and Tuttle[15] found the angle between the optic axis and the pole of the deformation lamellae to vary with the angular distance from the optic axis of the grain to the *B*-fabric axis ("*B*" is written "*b*" in this paper). In addition, they tabulated the solid angle formed by the planes containing the optic axis and poles to two sets of deformation lamellae from the same grain. If deformation lamellae are translation glide-planes containing the glide-direction $[m:r]$, then this angle is 60°. No evidence of this 60° angle was found.

[13] Pp. 95–96 of ftn. 7.

[14] "Quartz Deformation and Crystal Structure," *Amer. Min.*, Vol. XXIV (1939), pp. 351–68.

[15] P. 101 of ftn. 7.

The deformation lamellae do form more frequently at low angles to the basal pinacoid. The distribution of angles (optic axis to pole of deformation lamellae) of Ingerson and Tuttle and of Fairbairn, tabulated in Figures 10 and 11 of Ingerson and Tuttle,[16] were substantiated by measurements on the Baraboo quartzite. In addition, the perpendicular distance between individual lamellae was measured. The spacing varied between 2.5×10^{-4} and 17×10^{-4} cm., with a mean value of 8.3×10^{-4} cm. These values agree in magnitude with the observed spacing of slip-planes in metallic crystals.

Ingerson and Tuttle relate the deformation lamellae to the fabric axes; that is, the intermediate-strain axis is parallel to the lamellae (or the lamellae poles lie in the *a*–*c*-fabric plane). Ingerson and Tuttle have further pointed out that if the lamella pole and the optic axis of quartz are plotted for an individual grain and are joined by a great circle, the pole to the lamella always lies between the optic axis and the *a*-fabric axis (Fig. 3), that is, the great circles joining optic axes and deformation-lamellae poles always "point" to the *a*-fabric axis.

[16] P. 99 of ftn. 7.

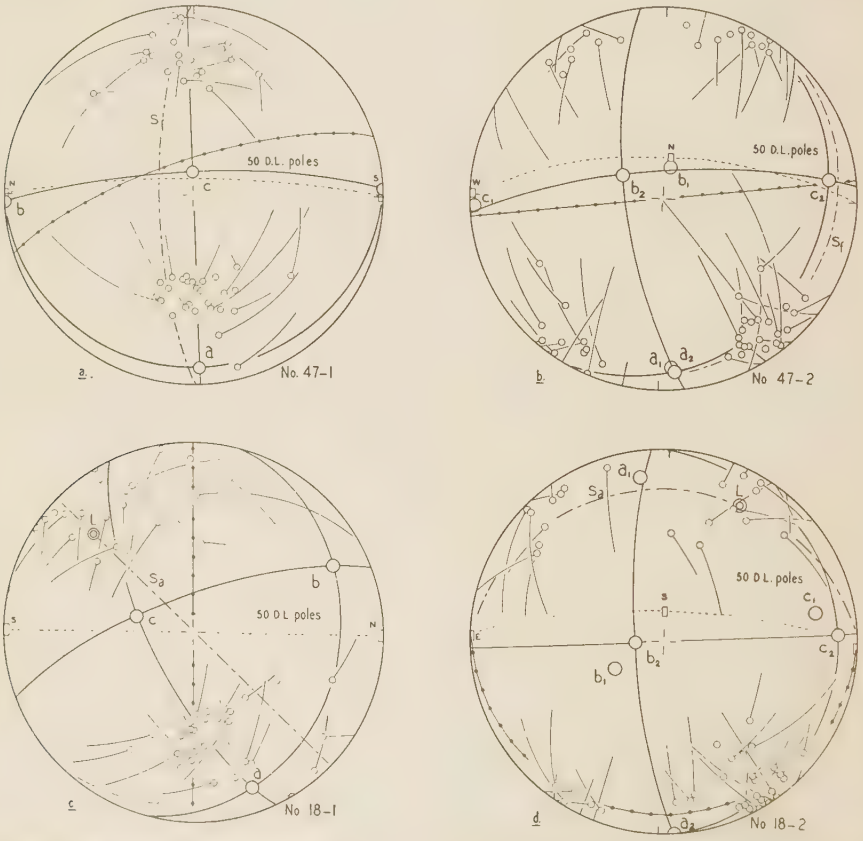

FIG. 3.—From Sample 47 two perpendicular sections have been cut, 47-1 and 47-2. The *a*-, *b*-, and *c*-fabric axes were determined independently in each section from the pattern of the poles of the deformation lamellae. The fabric axes determined from 47-1 are plotted on the projection for 47-2 and labeled as a_1, b_1, c_1. The above also applies to the two sections from Sample 18. The top of the bedding is to the south in Sample 18.

No consistent relationship was found in the Baraboo quartzite between the *a*–*b*-fabric plane determined in the field from the macrofoliation surfaces and the fabric axes determined from the pattern of the deformation lamellae. To avoid confusion of terminology, the *a*-, *b*-, and *c*-fabric axes are directions determined according to Ingerson and Tuttle from the pattern of the deformation lamellae. Megascopic foliation surfaces in all examples are here designed as *S*-surfaces, with subscripts to denote type of *S*-surface. Figure 14 shows the variation in the fabric axes as determined from the deformation lamellae over the outcrop area of the Baraboo quartzite. The interpretation of this pattern will be discussed later.

In most samples the poles of the deformation lamellae are concentrated in two small maxima, and the *a*-, *b*-, and *c*-fabric axes can be critically located with reproducible results from variously oriented thin sections of the same sample and from different areas of the same thin sections. Two examples of this for a pair of mutually perpendicular thin sections from the same sample are given in Figure 3.

As deformation of the aggregate increases, an individual grain will be subjected to a changing-stress field. Deformation of a particular grain and deformation of its neighboring grains will alter the local stress pattern. A wide range in character, strength, and deformation of the deformation lamellae themselves is observed in an increasing-deformation field. Increasing deformation, of course, applies to a sequence of changes as observed in a series of rock specimens. In addition to the location of the *a*-, *b*-, and *c*-fabric axes, therefore, considerable evidence concerning the deformation can be obtained from the variation and character of the deformation lamellae. Ingerson and Tuttle[17] indicated the above but did not elaborate.

The following detailed observations serve to illustrate the variations in the character of the deformation lamellae and in the pole pattern of the deformation lamellae. They are from samples containing negligible amounts of sericitic material, unless otherwise indicated.

1. The samples which exhibit the most precisely oriented pattern of poles of the deformation lamellae are those whose quartz grains show slight undulatory extinction, no noticeable dimensional elongation, distinct original boundaries with secondary enlargement, and rare other intragranular discontinuities. From the above, it appears that in an increasing-deformation field these lamellae are the first deformation structures to appear. Many examples can be found in which the deformation lamellae cross the boundary from the original grain into the region of secondary enlargement. Most of the deformation lamellae, therefore, followed the secondary enlargement. The exact relations between the development of undulatory extinction and the formation of deformation lamellae is difficult to evaluate, but grains exhibiting deformation lamellae also show some slight undulatory extinction. Sample 47, whose pole pattern of deformation lamellae is shown in Figure 3, is an excellent example of the above.

2. Curved deformation lamellae are found in samples exhibiting strong undulatory extinction, which has discontinuities subparallel to the optic axis, seldom observed original grain boundaries, and a noticeable grain dimensional elongation. The orientations of the great circles joining the optic axes and the poles of the deformation lamellae vary from the

[17] P. 105 of ftn. 7.

ideal examples shown in Figure 3. Figure 4, Sample 9, is the pole pattern of a sample showing the above features.

3. One large diffuse maximum of the poles of the deformation lamellae and several smaller minor maxima are shown by samples exhibiting the partial breakdown of the original grains to smaller elements, rare original grain boundaries, and a pronounced grain dimensional elongation. The *a*-, *b*-, and *c*-fabric axes are difficult to locate from the pole pattern. The deformation lamellae in the elongate grains are oriented about 30° to the elongation (Fig. 5, Sample 28). The unequal development of the pole maxima of the deformation lamellae could be explained in the following ways:

a) The deformation lamellae tend to form subperpendicular to the *c*-axis of the grain. With certain patterns of preferred orientation of the *c*-axes, one set of deformation lamellae would be more common than the other. Diagrams showing a definite *c*-axis preferred orientation can possibly be correlated with the deformation lamellae pole pattern (Fig. 5).

b) The deformation lamellae are re-

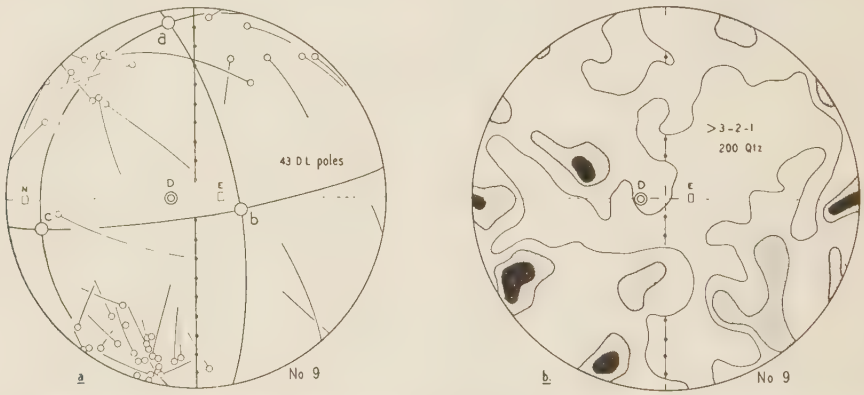

FIG. 4.—Pattern of poles of deformation lamellae in which one maximum is stronger than the other. A weak optic-axes fabric from random grains indicates a possible correlation.

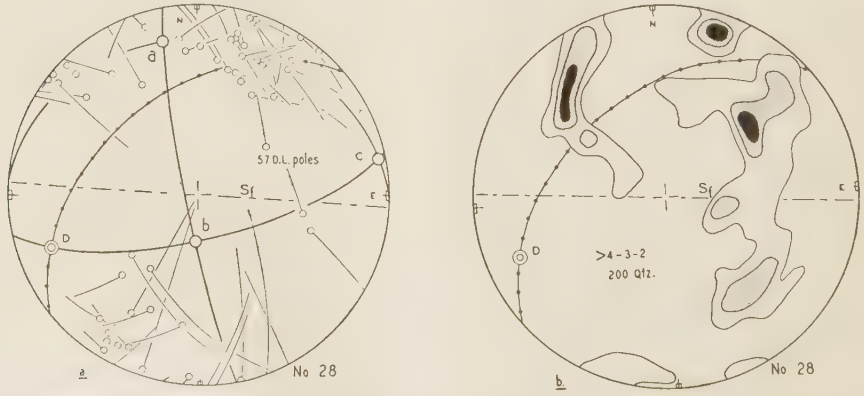

FIG. 5.—One large diffuse maximum of poles of the deformation lamellae, one or possibly two small maxima, and many aberrant lamellae make the choice of the fabric axes difficult. The pronounced dimensional elongation and the definite preferred orientation of the optic axes is not directly correlative with the deformation lamellae pattern.

lated to the macroshear surfaces, one of which is better developed than the other. No constant relation was found between macrofoliation surfaces and the planes of deformation lamellae.

c) The deformation lamellae are related to the dimensional grain elongation, i.e., metamorphic dimensional grain elongation, which, in turn, is related to the optic-axes fabric. In rocks showing the most highly oriented and symmetrical pattern of poles of deformation lamellae, the deformation lamellae appear to form subperpendicular to the long-dimensional axis of the grains. This is "according to Hoyle" because grains which are nonequant suffer, on the average, the greatest bending parallel to their long dimension. If actual movement, either by gliding or by fracture, takes place along the deformation lamellae, then, under continued deformation, the individual grains are elongated in a direction in the plane of the deformation lamellae. With infinite elongation the greatest dimensional elongation of the grains would become parallel to the set of deformation lamellae causing the elongation. This hypothesis is crudely verified by measurements of the angle between the elongation and the deformation lamellae in specimens exhibiting various amounts of grain elongation. In addition, the grain elongation can be expressed as a flattening, which can be taken as two principal directions of elongation. The better-developed system of deformation lamellae would then logically be subparallel to the greater axis of elongation. In only one example—Sample 55, Figure 6—flattening of the quartzite grains was observed, and the above relation was not verified. In this example, however, one set of deformation lamellae is perpendicular to the flattening and one subparallel.

The logical conclusions are twofold. In very elongate grains in which the deformation lamellae are oriented at small angles to the dimensional elongation, the observed dimensional elongation could have been accomplished by gliding along the deformation lamellae. On the other hand, if the deformation lamellae are roughly subperpendicular to the long-dimensional elongation of the grains, then the deformation lamellae were formed after the event which caused the grain to be dimensionally elongated.

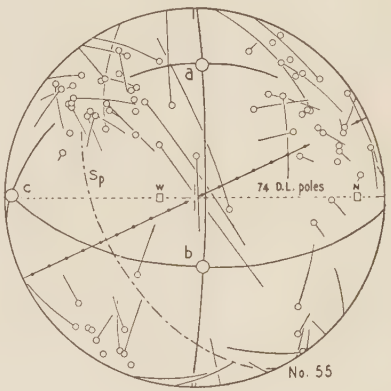

FIG. 6.—Conglomeratic quartzite (Dake?) in which the grains are flattened. In the surface of flattening, S_p, the greater elongation approximately coincides with the bedding. The deformation lamellae and the flattening are possibly related in that one pole maximum coincides with the surface of flattening and the other is approximately perpendicular.

The above interpretations are undoubtedly related but are difficult to demonstrate because neither the orientation of the forces applied nor the number of deformations is known and also because the measurement of average grain elongation in the thin section is difficult and based on the assumption that the grains are cylindrical in shape.[18] Since the major axis of metamoprhic dimensional grain elongation apparently lies

[18] Kurt E. Lowe, "A Graphical Solution for Certain Problems of Linear Structure," *Amer. Min.*, Vol. XXXI (1946), pp. 425–34.

close to the bedding surfaces (Fig. 14, Samples 9, 55, 35, 28, 3), it seems logical to assume that the stress causing the elongation has acted along the bedding surfaces. The pattern of deformation lamellae should then be related to the bedding and to the axial-plane foliation, which is, in turn, related to the bedding. No such relation is found consistently over the region. A possible explanation is that the pattern of deformation lamellae represents a later deformation imprinted

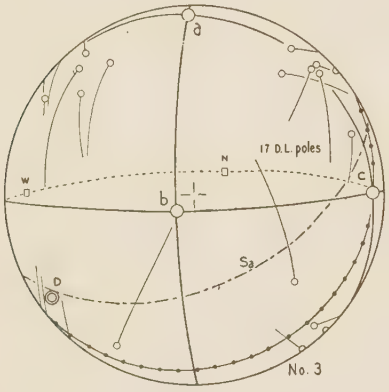

FIG. 7.—Pole pattern of deformation lamellae from a sericite schist layer. The few deformation lamellae observable adequately bring out the pattern. No relation is apparent between the pole pattern and the axial-plane foliation, S_a, observed from the outcrop, in the hand sample, and in the thin section. For another example of the same rock type, see Sample 18, Fig. 3*c* and *d*.

on an earlier pattern of metamorphic structures. Samples 3 and 18, Figures 7 and 3, are from sericite schist members of the Baraboo quartzite which exhibit marked axial-plane foliation. The fabric planes determined from the deformation lamellae do not bear any detectable relation to this foliation. In their examples Ingerson and Tuttle have demonstrated that the fabric axes determined from the deformation lamellae are related to the macrofabric axes, that is, the *a*–*b*-fabric plane determined from the deformation lamellae is parallel to the axial-plane foliation. If we accept their data, then the fabric axes determined from the deformation lamellae in the Baraboo quartzite are related to a different system of forces than those which resulted in the axial-plane foliation.

4. In several pole patterns of deformation lamellae (Samples 5 and 6 in Fig. 14; the pole pattern for Sample 6 is shown in Fig. 8), the poles form a girdle about the *a*-fabric axis. This girdle has an apical angle of about 80°. The pattern, therefore, has one degree of freedom about the *a*-fabric axis; thus the *b*- and *c*-fabric axes cannot be uniquely determined. Either of two explanations appears possible: that this pattern represents true biaxial strain or that this pattern represents two or more deformations, during which the *a*-fabric has remained essentially constant in direction but with various directions of the *b*- and *c*-fabric axes.

5. Deformation lamellae whose planes are marked by a thin film of brown material are recognized. Ingerson and Tuttle,[19] when they can detect no difference in index of refraction between the lamellae and the rest of the grain, call this type of lamella "relict." Very minute changes in the density of the brown film in one lamella can be traced through the set of the lamellae, subperpendicular to the lamellae, subparallel to the optic axis of the grain, and parallel to the discontinuities in the undulatory extinction. Hietanen describes a quartzite in which the deformation lamellae, termed "Böhm lamellae" in her paper, are curved, showing a wavelike pattern. Her diagrams[20] illustrate the change in texture of the brownish material along the lamellae, as described above, at the positions of curvature of the lamellae. Curvature of the deformation lamellae in

[19] P. 95 of ftn. 7. [20] Pp. 39–40 of ftn. 8.

the Baraboo quartzite and/or changes in the density of the brown film along the lamellae coincide with discontinuities in the undulatory extinction subparallel to the optic axis.

Hedvall and Sjöman[21] have shown that, at temperatures above the inversion point of quartz, Fe_2O_3 diffuses into the quartz lattice at a rate measurable in the laboratory. With sufficient time and perhaps in the presence of impurities, it is entirely possible that appreciable diffusion occurs at lower temperatures and that the brown films marking the deformation lamellae have originated in that manner.

6. Two sets of deformation lamellae rarely occur in a single grain. When observed, one set is more pronounced and appears to cut the other set. This observation does not necessarily imply two deformations, because two sets of deformation lamellae in the same grain could be explained as the result of local perturbations in the stress field during the same deformation.

If the relict deformation lamellae could be separated in a particular sample from deformation lamellae not showing the brown film and if the relict lamellae were cut by the nonrelict lamellae and if the pole patterns of the two types of lamellae were consistently different and if the regional configuration of the rocks could be correlated with two distinct deformation-lamellae patterns, then perhaps multiple deformations could be inferred. A lengthy attempt was made to achieve this result, but without success.

Summarizing the foregoing, it is possible to achieve a qualitative estimate of the intensity of the local deformation from the pattern of the deformation-lamellae poles and from the character of the deformation lamellae themselves. In an increasing intensity of deformation the following varieties appear:

1. *Straight deformation lamellae.*—These are usually in the central portions of the grains; and they are roughly perpendicular to the long axes of the grains; the pole pattern of the deformation lamellae is clear cut, with two well-developed maxima approximately 80° apart; the pole of a particular set of deformation lamellae always lies between the *a*-fabric axis and the optic axis of the particular grain.

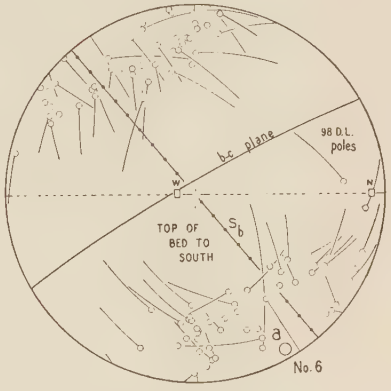

FIG. 8.—Pattern of poles of deformation lamellae in which the poles are distributed in a small circle about the *a*-fabric axis.

2. *Curved deformation lamellae.*—These lamellae appear with the curvature along planes subparallel to the optic axis and parallel to the discontinuities in undulatory extinction; the relation between the deformation lamellae and dimensional grain elongation is obscure; the pole pattern of the deformation lamellae is more diffuse than in the above examples, but the two maxima are clearly recognizable.

3. *Curved deformation lamellae as above.*—Dimensional grain elongations tend to be at small angles to the plane of the deformation lamellae; the pattern of poles to the deformation lamellae is dif-

[21] P. 212 of ftn. 12.

fuse, so that the fabric axes are determined with considerable question.

The above analysis applies only to "pure" quartzites, that is, each quartz grain is bounded by quartz grains with only small amounts of other material, such as sericite, in the interstices among the quartz grains. The stresses are then transmitted principally from quartz grain to quartz grain. As the amount of sericite, for example, is increased, part of the change in shape of the deforming aggregate is borne by the sericite. With sufficient admixture of sericite, such that the quartz grains are no longer in contact with one another, the major portion of the change in shape of the aggregate in deformation is accomplished by change in the sericite, the quartz grains acting as rigid bodies in a viscous fluid.

The study of the deformation lamellae in the Baraboo quartzite indicates the need for a better understanding of the conditions of their formation and of their exact nature. Only by producing them experimentally can the relation between the forces and the ensuing pattern be determined. If this could be accomplished, deformation lamellae should be one of the more powerful tools in the study of deformed rocks.

II. DEFORMATION BANDS

A detailed study of the variation in the orientation of the optic axis in individual quartz grains of the Finnish quartzites has been made by Hietanen.[22] She plotted the orientation of the optic axis of a particular grain on an enlarged trace of the grain outline. These plots show the angular limits of the undulatory extinction and demonstrate that the extinction varies continuously over certain limited areas, which are separated from one another by discontinuous changes in the undulatory extinction. These discontinuities, in all her examples, are subparallel to the general orientation of the optic axes of the particular grain and impart to the grain, under crossed nicols, a banded appearance. Most of Hietanen's examples are highly metamorphosed, and the grains exhibit a banded appearance over the entire grain.

In the Baraboo quartzite, however, other discontinuities in the undulatory extinction are found. It is these discontinuities, and not the ones subparallel to the optic axis, that are termed "deformation bands." Adams[23] noted similar structures in vein quartz and described them as follows:

> The latticed structure shown by inclusions may sometimes be seen under crossed nicols (Pl. XXVI., *F*). The features brought out by this photograph are: (1) each single apparent veinlet consists of a thread of quartz which disagrees in extinction position with the parent crystal; (2) the crystallographic orientation of the quartz in parallel threads, the traces of roughly parallel planes, is the same; (3) the orientation in one set of planes is not the same as in the other set.

Deformation bands are infrequent in the Baraboo quartzite, but in two examples they are common (Samples 38 and 16, Figs. 9 and 10). The shift in the optic axis from grain to band is very small, so that the bands are observed only close to the extinction position of the grain. For fifty-four measured shifts in orientation from grain to band, the mean shift was 5°.9, with a standard deviation of 4°. The mode was in the 2°–4°-class interval, however, indicating that a few large values have substantially increased the mean. In addition, there is a suggestion that the distribution is bimodal. The surprising thing about the change in orientation is that in most examples the change is usually in the same rotational sense. In

[22] Pls. I–VII of ftn. 8.

[23] P. 648 of ftn. 9.

Sample 38, Figure 9*b*, for example, the sense of rotation from grain to band indicates that the younger beds to the south have moved upward with respect to the older beds to the north. In Sample 16, Figure 10*b*, however, the relationship is not clear cut. In many examples the difficulty is in determining which part of the grain is band and which part of the grain is the supposed undeformed part.

It is not possible to determine the relation between the deformation bands and the structure of the quartz, because the spatial orientation of the bands cannot be optically determined. The traces of the bands in the plane of the thin section, however, tend to be perpendicular and parallel to the optic axes. In addition, in Sample 38, Figure 9*b*, the traces of the deformation bands are mainly at a small angle to the bedding. If the bedding surface has acted as the shearing surface, then the relation of the traces of the deformation bands to the bedding is similar to the results of experimental work of W. Riedel, which has been discussed by A. Nádai.[24]

Riedel sheared plastic clay and found

[24] *Plasticity* (New York: McGraw-Hill Book Co., 1931), p. 330.

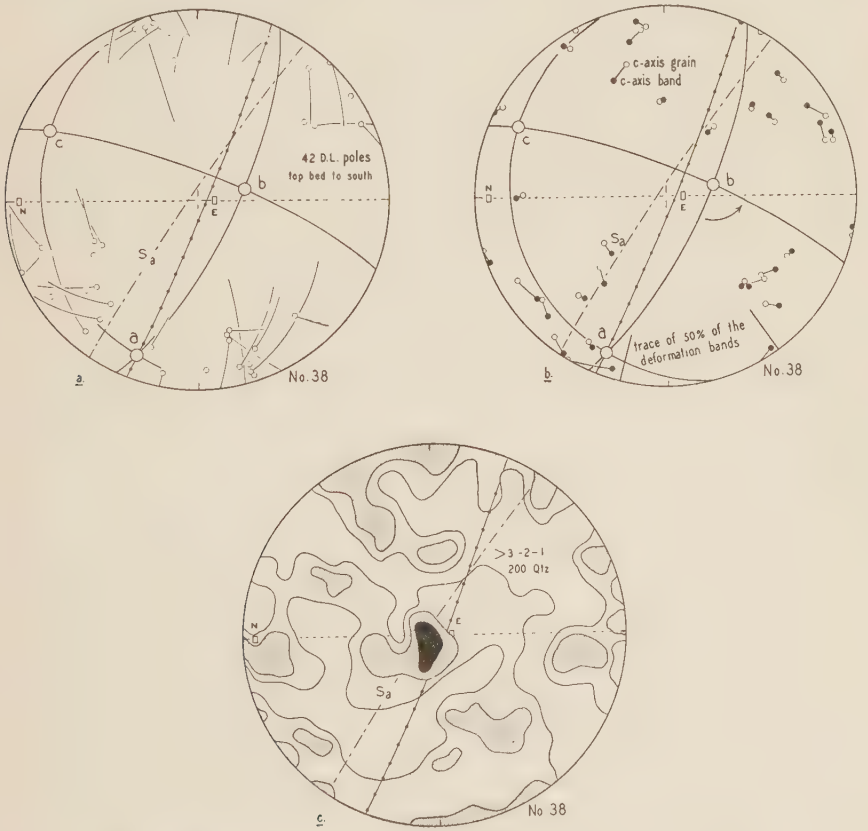

FIG. 9.—*a*, Pattern of poles of the deformation lamellae. The *a*–*b*-fabric plane is close to the axial-plane foliation determined in the field, from the hand sample, and in the thin section. *b*, Change in orientation of the optic axis from the major portion of a grain to the deformation band. All shifts are in the same rotational sense. *c*, Slight preferred orientation of the optic axes. The weak north-south girdle and the maximum at the center of the projection are reproducible.

that shearing cracks formed about 12° to the direction of shear. These are oriented similarly to the traces of the deformation bands in Sample 38, if the bedding plane is taken as the shear plane and the direction of shear is taken from the change in optic orientation from grain to band.

These bands need not be simply deformed quartz but could be a stress modification of SiO_2.

III. MICROFRACTURES

Microfractures are observed in most examples of the Baraboo quartzite. These fractures can be divided into those which are confined to individual crystals and those which pass through the aggregate of crystals without deviation at the crystal boundaries. It is the latter which exhibit a very strong preferred orientation and whose orientation pattern correlates very closely with the fabric axes determined from the pattern of the poles of the deformation lamellae. Sample 58, Figure 11, exhibits the close correlation of deformation-lamellae and microfracture patterns. The maximum of the poles of the microfractures lies but a few degrees from the *a*-fabric axis, determined independently from the deformation

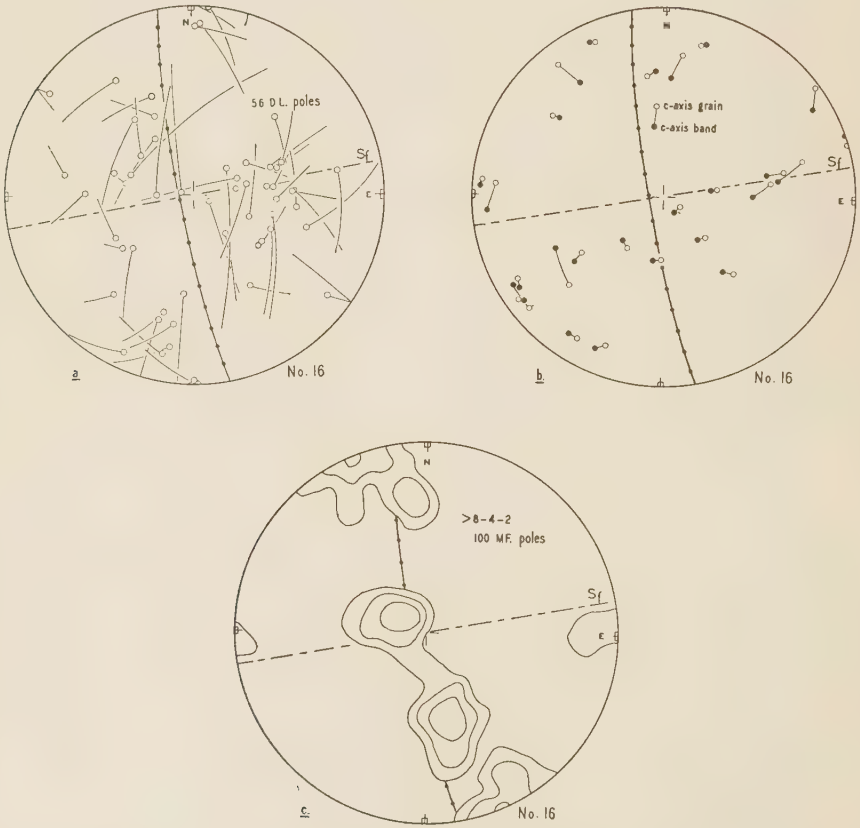

FIG. 10.—*a*, Diffuse pole pattern of deformation lamellae. The fabric axes for this sample shown in Fig. 14 are questionable. *b*, Change in orientation of the optic axis from grain to deformation band. Slight tendency for rotation to the southwest. The top of the bedding is to the east, and the younger beds have moved up with respect to the older. *c*, Poles of microfractures form a partial girdle, which is perpendicular to the shear fractures and subparallel to the bedding.

lamellae. A corresponding relation is shown in Sample 21, Figure 12. These two examples make it difficult to avoid the inference that the deformation lamellae and the microfractures are both related to the same set of external forces. In addition, since the deformation lamellae in the Baraboo quartzite are not consistently related to the bedding and the foliation, the microfractures are not so related.

The principal set of microfractures in the foregoing two examples and in all examples observed in the Baraboo quartzite are oriented very close to the *b*–*c*-fabric plane determined from the deformation lamellae. They are, therefore, termed, "*b*-*c* microfractures." Since the *a*-fabric axis is generally close to vertical, the *b*–*c*-fabric plane and the *b*-*c* microfractures are close to horizontal. In one sample, however—Sample 7, Figure 14—the *a*-fabric axis, determined from the deformation lamellae, lay close to the horizontal. The maxima of the poles of microfractures from this sample followed the above examples and coincided with the *a*-fabric axis.

In several patterns of poles of microfractures, two maxima are present. One

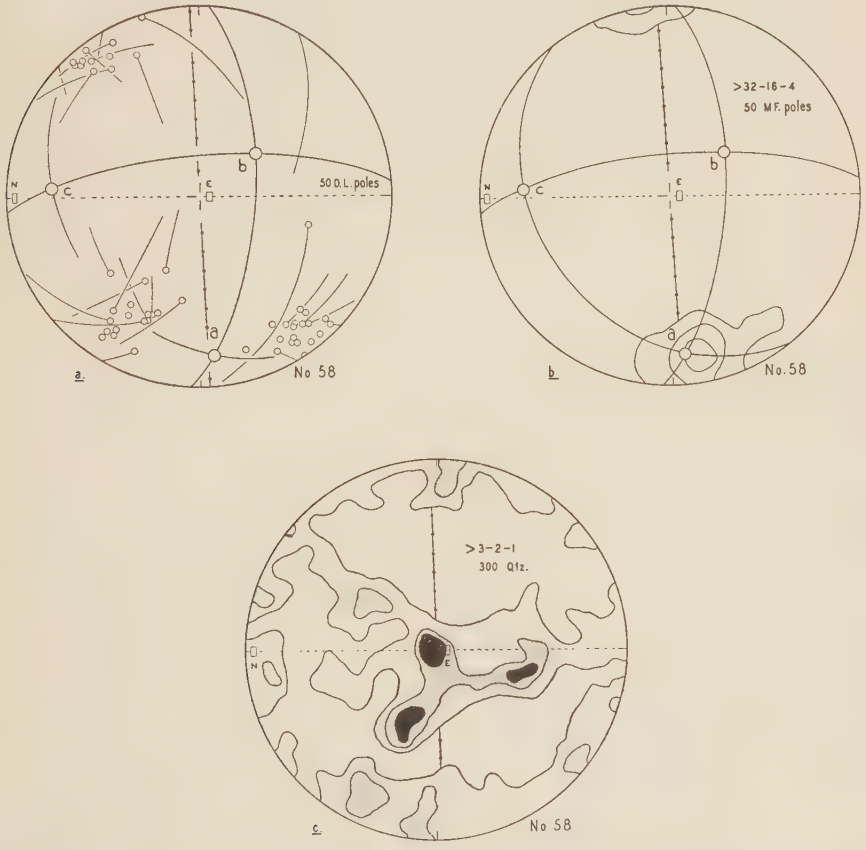

FIG. 11.—*a*, Symmetrical pole pattern of deformation lamellae, giving accurate location of the fabric axes. The sample is from a massive quartzite. *b*, The maximum of poles of microfractures is a few degrees from the *a*-fabric axis determined from the deformation lamellae. *c*, Weak north-south optic-axis girdle, partial horizontal girdle, and maxima close to axis of the weak north-south girdle.

maximum is close to the *a*-fabric axis, the other is weaker and close to the *b*-fabric axis. This type of pattern is shown in Sample 21, Figure 12, referred to above. These latter microfractures are termed "*a-c* microfractures." No examples were found in which *a-c* microfractures were present and *b-c* microfractures absent. In addition to the above two maxima, a few samples exhibit rare microfractures in the *a–b*-fabric plane.

Sample 16, Figure 10, evidences a partial girdle of poles to microfractures. O. F. Tuttle[25] in an abstract of his study pole girdle observed in Sample 16 is approximately east-west, corresponding closely to the strike of the region and perpendicular to the ever present east-west shear fractures. It was not possible to correlate the microfractures with the deformation lamellae in this sample because of the diffuse pattern of poles to the deformation lamellae.

The brief study of the microfractures in the Baraboo quartzite indicates that microfractures can be correlated with the pattern of the poles of the deformation lamellae and that *b-c* microfractures

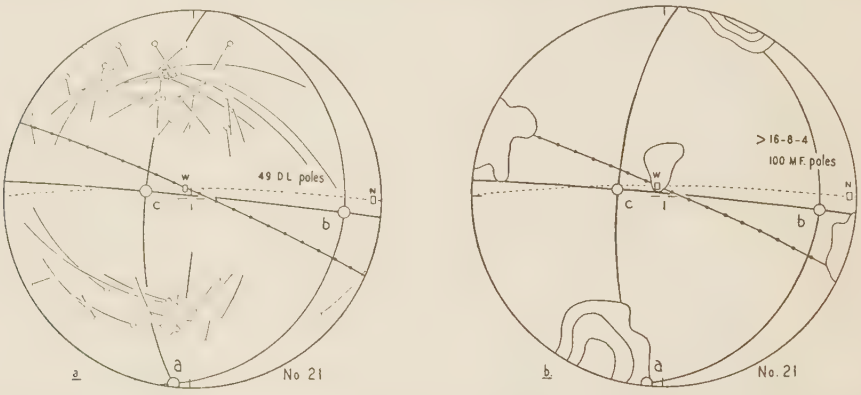

FIG. 12.—*a*, Symmetrical pole pattern of deformation lamellae. *b*, Three maxima of poles of microfractures at right angles. The principal maximum is close to the *a*-fabric axis determined from the deformation lamellae.

noted that in the rocks of the Washington area planes of inclusions passing through grain boundaries (termed "microfractures" in this paper) are not in agreement with local structure but are uniform over 15 or 20 miles. Also, he says that, in drag folds, planes of inclusions develop in shear directions and that one set predominates. Further, he observed that poles of the inclusion planes tend to be in a partial girdle about the fold axis. The axis of the microfracture

[25] "Structural Relations of Planes of Liquid Inclusions in the Crystalline Rocks of the Washington (D.C.) Area," *Amer. Geophys. Union Trans.*, Vol. XXVI (1945), p. 301.

are present if any microfractures are present. Since the pattern of the poles of the deformation lamellae do not correlate with the macroscopic foliation, the microfractures also do not so correlate.

IV. QUARTZ AND ZIRCON OPTIC-AXES FABRIC

The results of the study of the orientation of the quartz optic axes were discouraging. Many of the patterns are not reproducible from different parts of the same thin section. Three features of the weak patterns, however, do stand out and are usually reproducible: (1) a weak north-south vertical partial girdle; (2) a

small maximum close to the bedding and in the weak north-south girdle; (3) a small maximum close to the bedding and subperpendicular to the weak north-south girdle. In addition to the above features, it is possible in some examples to recognize a weak horizontal girdle.

The more definite examples of preferred orientation of the optic axes are found at the extreme eastern end of the outcrop area. Figure 5*b*, Sample 28, and Figure 13*a*, Sample 32, are two examples (Sample 32 is located near Sample 35, Fig. 14). No interpretation of any of the quartz-axes fabrics is attempted in this paper.

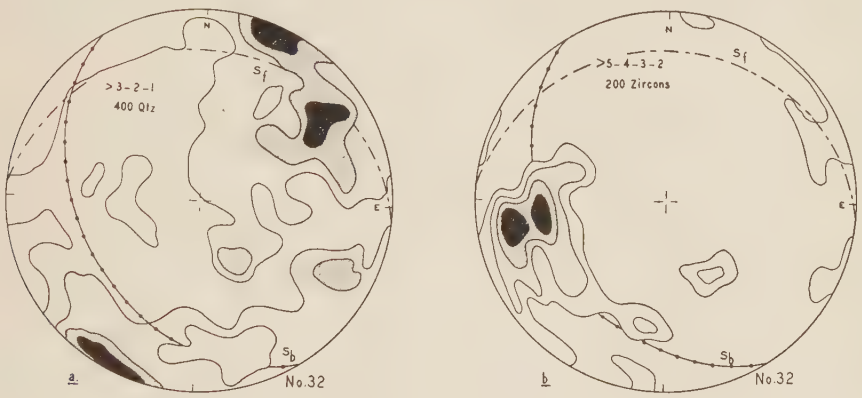

FIG. 13.—*a*, Pattern of optic axes of random quartz grains. A weak north-south girdle, dipping eastward, correlates with the pattern of Sample 28, Fig. 5*b*, which is on the south limb of the nose of the syncline. *b*, Pattern of optic axes of the zircon grains.

An examination of the outcrops, hand samples, and thin sections in the eastern half of the region shows that the deformation and the degree of preferred orientation increase from west to east toward the nose of the synclinorium. Comparisons among the samples can be made only among those which contain roughly the same admixture of sericitic material. This will be restated in the summary.

A flood of zircon grains was found in Sample 32, Figure 13*b*, located near Sample 35, Figure 14. The zircons occur in hematite laminae which are interbedded with laminae of quartz grains. The laminae are roughly 1 mm. thick. A fabric diagram was constructed for the optic axes of 200 zircons. One large maximum is located along the bedding plane. The individual zircons are fractured, but all exhibit rounded boundaries, while the quartz grains, a fraction of a millimeter away, rarely exhibit an original boundary and have been dimensionally elongated. The zircons are embedded in hematite (probably originally detrital iron oxide), and their orientation could have been accomplished by the dimensional orientation of the rigid zircons in a softer medium—i.e., hematite. This interpretation, of course, implies a correlation between the optic and the dimensional grain axes.

V. DIMENSIONAL GRAIN ELONGATION

The true spatial distribution of the axes of grain elongation is impossible to determine uniquely from thin-section studies. Lowe[26] determined a mean lineation from variously orientated outcrop surfaces of granite by assuming that the

[26] Ftn. 18.

grains are cylindrical in shape. In addition, he says that he has applied the same procedure to variously oriented thin sections of the same sample apparently by noting the modal direction in each thin section. These assumptions are definitely not true for most minerals developed through dynamic metamorphism; and, even if they were true, it is not possible to determine the actual frequency distribution from the frequency distribution of its projections. The above technique, however, does give an indication of the most frequent elongation if the grains are roughly cylindrical in shape and was applied to a few examples of the Baraboo quartzite.

Only five clear-cut examples of grain elongation were encountered in the samples studied (Fig. 14). In all except one example, the major elongation of the grains trends in an east-northeast direction. This direction is also the approximate strike of the bedding and the axial-plane foliation. Most workers in structural petrology consider that the grain elongation is usually parallel to the intermediate strain axis of the deformation, that is, to the fold axis. If that is true in the Baraboo region, the grain elongation is the result of the major deformation, with a fold axis striking roughly east-northeast.

The relation between the grain elongation and the pattern of deformation lamellae has been mentioned before in connection with the deformation lamellae. The writer does not believe it feasible to determine the exact relations between deformation lamellae and elongation from the Baraboo region, because we are not sure of the number of deformations, the orientation of the forces causing the deformation, etc. A laboratory study and/or a field study in a region in which the boundary conditions are well known should indicate the solution.

SUMMARY

1. A study of Figure 14 indicates that the strike of the *a*–*b*-fabric plane, determined from the pattern of the deformation lamellae, varies over the synclinorium and, with very few exceptions, cuts across the strike of the bedding and foliation. If these fabric directions are found in other regions to correlate with the foliation, as has been reported by Ingerson and Tuttle, then the patterns of deformation lamellae in the Baraboo quartzite represent a deformation different from that which resulted in the macrofoliation.

On the other hand, the *a*-, *b*-, and *c*-fabric directions so determined could represent the local strain axes of the deformation, independent of the discontinuous mass movement along bedding surfaces. Strata containing axial-plane foliation were initially regions of weakness, and it is along these surfaces (for a wide range in the orientation of the applied forces) that the majority of the mass transport occurs. Referring again to Figure 14, we see that most of the *a*–*b*-fabric planes are subperpendicular or subparallel to the bedding and the foliation surfaces. If we think of the whole structure as having been formed in one deformation, the regions in which the *a*-*b* fabric is subperpendicular to the bedding and foliation are regions of approximately horizontal compression parallel to the bedding and foliation. Conversely, regions in which the *a*–*b*-fabric plane is subparallel to the bedding and the foliation are regions of approximately horizontal stretching parallel to the bedding and the foliation. This latter example is the usual concept of the orientation of the strain in a simple fold. The above-described regions of

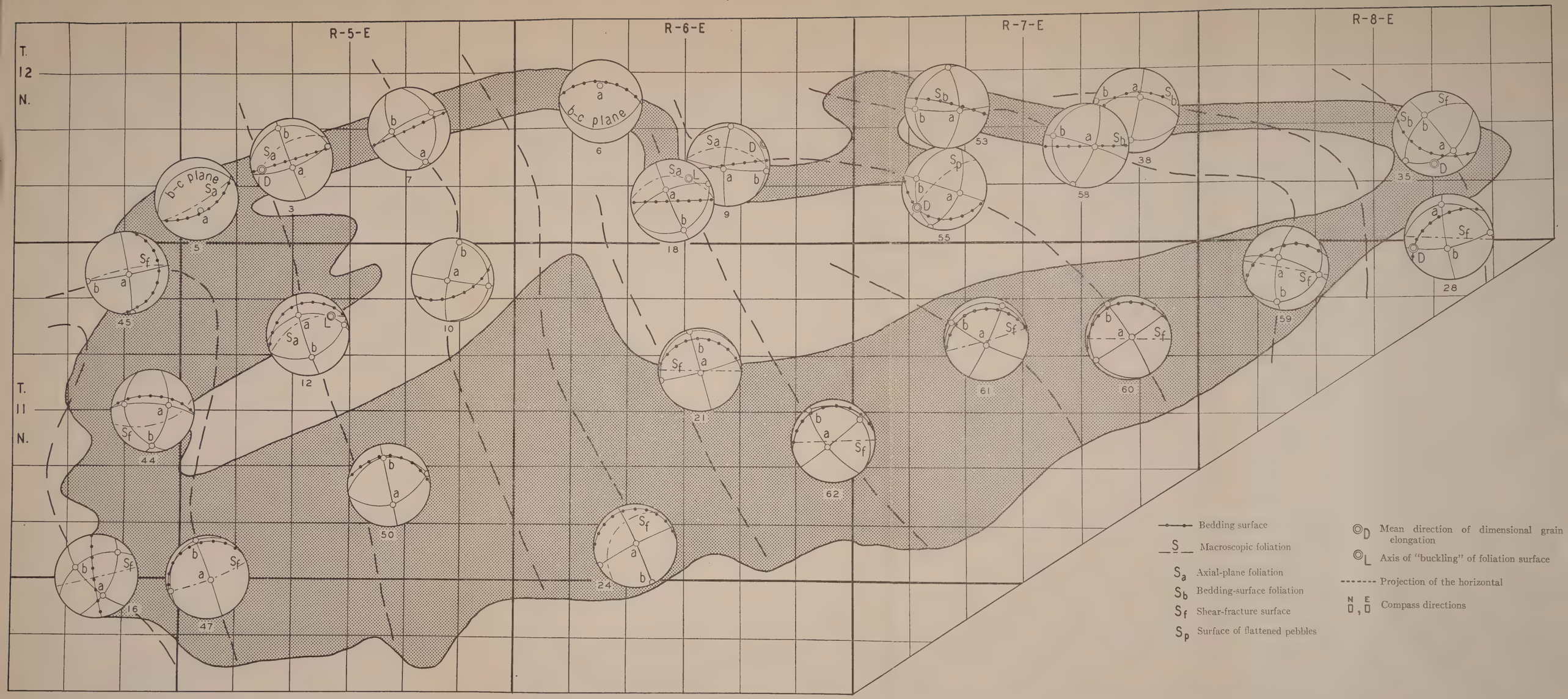

FIG. 14.—Generalized outcrop area of the Baraboo quartzite (modified from A. Leith). The *a*-, *b*-, and *c*-fabric axes were determined from the pattern of the poles of the deformation lamellae. The dashed lines represent the trend of the strike of the *a*–*b*-fabric plane so determined

compression and stretching in the bedding and/or foliation plane can be thought of as regions of convergence and divergence perpendicular to the principal direction of movement. This phenomenon is recognized in ocean currents and atmospheric currents. Koenigsberger and Hungerer,[27] studying both elastic and plastic bodies, found that in the bending of prisms a secondary fold develops, with a larger radius of curvature than the primary fold and at right angles to the primary fold. These secondary folds have long been recognized by the structural geologists and are called "saddle folds" or "cross-folds." The orientation of the fabric axes determined from the deformation lamellae, therefore, could possibly have resulted from the secondary stresses produced from a series of initially east-northeast folds.

The writer has no preference for either of the above two interpretations. The field problem is always tremendously complicated, and it is almost pure fantasy to interpret a complicated structure in simple terms when we are not even able to interpret a simple structure in complicated terms.

2. In addition to the pattern of the fabric axes determined from the deformation lamellae, the following observations point toward an interpretation of structure that would necessitate more than one period of deformation:

a) Two or more periods of quartz veining are separated by at least one period of deformation.

b) Shear-joint surfaces or perhaps shear fractures in the western half of the region tend to be subparallel to the strike of the *a*–*b*-fabric plane determined from the deformation lamellae.

c) There is chevron folding, that is, buckling, of the axial-plane foliation.

3. A study of a series of samples from the eastern half of the region (in particular, from Sample 53 eastward, in the north range) indicates that the intensity of the deformation has increased toward the nose of the synclinorium. This is evidenced by the following observations:

a) Decrease in the percentage of grains showing original boundaries
b) Increase in the total angular variation in the position of the optic axis in individual grains
c) Increase in the number of grains showing discontinuities in the undulatory extinction
d) Increase in the number of grains which have been broken down into smaller units
e) Increase in the degree of preferred orientation of the optic axes

It is again emphasized that comparisons among samples can be made only when all the samples are of the same composition, that is, in this example, the amount of admixed sericite relative to the quartz. Sericite is a good lubricant, and, when admixed in sufficient quantities to the quartz grains, it will account for the majority of the change in shape of the mixture during deformation.

4. This study has convinced the author that structural petrology needs a theoretical foundation based on experimental deformation of solids and consistent with the physical and chemical concepts of the structure of matter.

[27] A discussion of their work is given by H. W. Fairbairn, *Structural Petrology of Deformed Rocks* (Cambridge, Mass.: Addison-Wesley Press, 1942), pp. 78 and 96.